The Nutrient Cycle:

Key to Continuous Forest Production

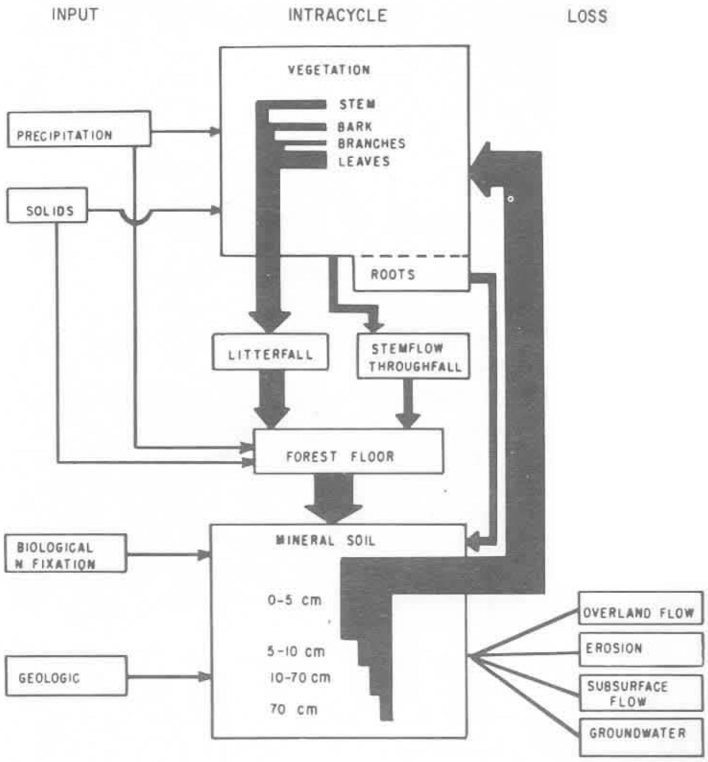

Figure 1. The nutrient cycle in a loblolly pine stand.

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ABSTRACT—Nutrient conservation should be considered along with methods for increasing biomass harvests. In a 16-year-old loblolly pine plantation, harvesting the aerial portion and larger roots of trees removes 12 percent of the total N, 8 percent of the extractable P, and 31 percent of the extractable K from the site. Only one-third the quantity of nutrients are removed by harvesting only debarked pulpwood. There is an optimum annual biomass production on each site that depends on nutrient availability, in addition to other growth amenities. Management practices that take the nutrient cycle into account may be the most advantageous economically over one or more rotations.

The three major factors required for plant growth—sunlight, water, and nutrients—may be manipulated, to some extent, to regulate rate of growth. Each factor is also renewed: sunlight, daily; water, usually every week or two; nutrients, anywhere from several to hundreds of years. The key to an adequate supply of nutrients is the nutrient cycle, which permits reuse of nitrogen, phosphorus, and potassium (N, P, K) and other elements.

There is a global nutrient cycle which often requires geologic eras for completion and consists of the movement of a nutrient from the terrestrial environment to the sea and return. Within this total cycle are secondary ones that are very important in tree growth. The nutrient cycle in the forest consists of a series of interdependent processes, generally thought of as a series of nutrient pools or components, such as soil or forest floor, connected by transfer paths (*Figure 1*). The rate of nutrient transfer from one pool to another varies between plant species, soils, and ecosystems; unusually slow or rapid rates often produce nutrient imbalances or deficiencies that are responsible for poor plant growth.

To study this process, we are focusing on the nutrient intracycle of a stand of loblolly pine (*Pinus taeda* L.) and the additions of nutrients to, and losses from this cycle. Loblolly was chosen because it is the most important timber producing tree in the South. The complete study includes the effects of site preparation, complete-tree harvest, and fertilization of this species on nutrient cycling in the Piedmont of North Carolina and South Carolina. Harvesting effects are discussed here.

The Forest Nutrient Cycle

The forest nutrient cycle has three segments: an input, an intracycle or system within which nutrient movement takes place, and an output (*Figure 1*). We can see how the cycle operates by examining some sources of nutrient input, the movement of nutrients within the cycle from one component or pool to another, and the ways in which nutrients are eventually lost from the system.

Inputs and losses.—Inputs to a forest system under normal circumstances are small quantities of nutrients usually sufficient to nearly balance losses. Major input comes as dissolved gaseous or solid materials in precipitation or in particulate matter that settles on the site. Most elements, such as phosphorus and calcium, are of low solubility and are added as particulates. Nitrogen and sulfur, however, enter the system as water-soluble gases or solids. Nitrogen in precipitation is primarily the result of atmospheric fixation, but other sources, including industrial operations and the release of ammonia from the soil, may be locally important. Gaseous sulfur compounds produced by the decomposition of organic materials and returned by precipitation are the most important source of sulfur, and industrial and geologic sources may augment the supply.

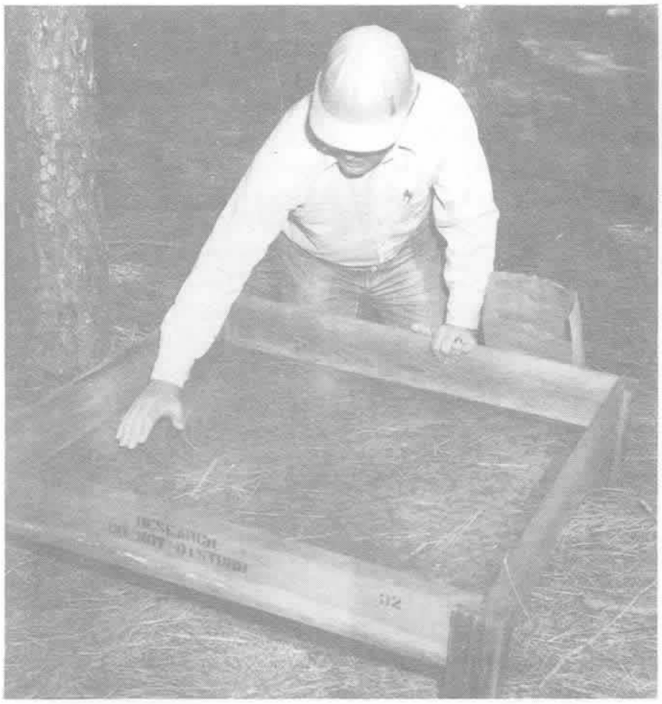
The fixation of molecular nitrogen by soil microorganisms may, under some circumstances, provide a major source of nitrogen. In the Piedmont, however, soil acidity and a low organic matter content probably limit fixation by free-living soil organisms to less than 1 kg/ha/year. In the loblolly pine system only small quantities of nitrogen are fixed by plants such as legumes. Geologic weathering of primary minerals is not an important source of nutrients over the short term. However, soil-forming processes in the solum and weathering of secondary minerals in the C horizon may yield important nutrient inputs. The addition of fertilizer and deposition by flooding can be important in some situations.

Natural losses from and inputs to a typical loblolly pine site approximately balance. The amount of nutrients leaving the site by any of the four avenues shown in *Figure 1* will depend on environmental conditions. Two additional ways nutrients are lost are by fire and biomass removal (harvesting). The largest nutrient drain or removal from the system may be from biomass harvest, especially if complete trees are harvested.

The intracycle.—Nutrients on a site are found in the vegetation, the forest floor, and the mineral soil. Examinations of the cycling (or movement) of each nutrient will not be undertaken but, in brief, each nutrient has a distinctive transfer rate owing to its chemical and physical characteristics and physiological function. These characteristics control the type of compounds in which the nutrient is found, and the rate at which the element may be recycled. For example, nitrogen can form mineral-organic complexes and require several decades for a complete cycle, while potassium, which is more often water soluble, is cycled many times more rapidly than nitrogen.

A Loblolly Pine Nutrient Cycling System

Site nutrients.—In the North Carolina Piedmont, trees in a 16-year-old plantation (site index 68 at age 25) with 2,243 trees/ha weighed 192.3 metric tons/ha[1] and contained 321 kg of N, 48 kg of P, 226 kg of K, and additional quantities of other elements essential to plant growth (*Table 1*). At this age approximately equal amounts of nutrients existed in the needles and in the stemwood, but the concentrations differed greatly. In September, when a large proportion of needles produced over two growing seasons were still on the trees, the needles weighed 8 metric tons/ha, whereas the stemwood weighed nearly 14 times as much. Thus, nutrient concentration in the stemwood is low relative to that in the needles. The proportion of nutrients in the various components changes as the trees age. For example, the proportion of nutrients incorporated into stems increases with tree age because stem weight increases (*1,2*).



Falling litter was trapped, collected, and analyzed to determine amounts of nutrients returning to the forest floor.

In the 16-year-old plantation, most of the nutrients were in the soil profile. The forest floor of the stand weighed 28 metric tons/ha and contained 307, 30, and 28 kg/ha of N, P, and K, respectively. Mineral soil, to a 70-cm depth, had a total N content of 1,753 kg/ha, and 371 and 404 kg/ha of extractable P and K, respectively (*Table 1*). Total P and K of the mineral soil were not measured, but are several times greater than the extractable quantities.

Nutrient additions and losses.—Under normal circumstances and over nongeologic time periods, additions and losses of nutrients from a site tend to balance one another. Most nutrients come to the site via rainfall and dust particles. At the site of the 16-year-old

Table 1. Distribution of tree biomass and nutrients in a 16-year-old loblolly pine plantation in the North Carolina Piedmont.

Component	Biomass	N	p[1]	K[1]
	T/ha	*kg/ha*		
Trees				
Needles	8.0	82	10	48
Branches	23.2	60	6	28
Stemwood	109.6	79	11	65
Stem bark	15.2	36	4	24
Root total	36.3	64	17	61
Total tree	192.3	321	48	226
Forest floor	—	307	30	28
Mineral soil, 0-70 cm	—	1,753	371	404
Site total	—	2,381	449	658

[1] *Total in vegetation and forest floor and extractable in mineral soil.*

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[1] *Conversion of kg/ha to lb/acre and metric tons/ha to tons/acre may be done by multiplying the metric values by 0.892 and 0.446, respectively.*

plantation, nutrients from this source add about 5.5 kg of N, 0.2 kg of P, and 1.5 kg of K/ha/year. These amounts can vary widely from area to area due to local conditions, but are probably representative of what may be expected in much of the southeastern United States. Fixation of atmospheric N by microorganisms also adds some N to the soil, but in most southern pine plantations this amounts to less than 1 kg of N/ha/year.

Geological weathering of parent material and release of nutrients by soil-forming processes are responsible for the conversion of unavailable mineral elements to a form that can be utilized by plants. Addition of elements to the nutrient pool by these processes has not been measured on this site but is low.

Since there is little erosion and surface runoff, most nutrient losses from the plantation would be due to leaching of mineral nutrients and denitrification of mineralized N. Leaching losses are believed to be small and of no great significance in the nutrient cycle of an uncut plantation.

Nutrient accumulation and intracycle transfer.—Data collected from plantations ranging in age from 4 to 39 years show that maximum nutrient accumulation in loblolly pine trees occurs between 10 and 15 years of age, about the time and shortly after the stand closes and fully occupies a site. At age 16, estimated annual uptake by the trees in one plantation was 117 kg N, 21 kg P, and 64 kg K/ha. Approximately half was required for new needles, one-tenth for stem increment, and the remainder for branches and roots. Until this stage of stand development, rapid increases in nutrient uptake and nutrient accumulation were complemented by increases in biomass, especially of needles. With increasing age, the nutrient uptake and accumulation rate in the stand will decrease due to reduced growth, mortality, and a reduction of readily available nutrients in the soil.

Nutrient accumulation in the forest floor is rapid during the first few years after stand closure and continues at a reduced rate until equilibrium is approached at about 30 years of age. In a 34-year-old stand thinned three times, the forest floor, measured by repeated samplings, weighed nearly the same as that in the 16-year-old stand. However, the amount of N, P, and K in the forest floor continually increased with age. This increase shows that organic decomposition is more rapid than nutrient release at this time and that nutrients are accumulated in the decomposition-resistant organic fraction of the forest floor.

At about the period of maximum accumulation, annual transfer of nutrients to the forest floor via litterfall and water dripping from vegetation or running down the tree stem (throughfall and stemflow) amounted to approximately 68, 9, and 28 kg/ha for N, P, and K, respectively. During the same period 25, 4, and 21 kg/ha of the same nutrients were transferred annually to the mineral soil from the forest floor. A second important source of nutrients transferred to the mineral soil was from decomposing roots. Roots added 49 kg of N, 12 kg of P, and 20 kg of K/ha/year, showing that at this stage of stand development cycling of nutrients through root decomposition was as important as cycling from the forest floor.

The sources of nutrients to site vegetation are inputs, mostly via rainfall and particulate matter, and nutrient pools already on the site. Rainfall and particulates contributed only about 5.5 kg of N, 0.2 kg of P, and 1.5 kg of K/ha annually over the plantation's first 16 years. If vegetation incorporated all input nutrients over the 16-year period, 233 kg of N, 44.8 kg of P, and 202 kg of K would still be required to balance the nutrients taken up by the growing vegetation. The source of most of these nutrients is the mineral soil. Between the ages of 5 and 15 years in one plantation, N in the top 70 cm of mineral soil decreased from 2,392 to 2,010 kg/ha, a loss of 382 kg/ha. Decreases of extractable P and K in the soil amounted to 3.4 and 48 kg/ha, respectively, over the 10-year period. However, larger amounts were removed. The small decrease in P and K in the surface 70 cm of mineral soil shows that an equilibrium is maintained between the extractable and total amounts of these elements when nutrients are removed at moderate rates. Some nutrients may be extracted from below 70 cm in the mineral soil.

The long-term ability of the mineral soil to supply nutrients to trees is related to the total supply of each nutrient and to the rate at which it becomes available. The continuous availability of ample nutrients is one factor in site productivity, but because nutrient availability varies greatly between stands and is not readily controlled, timber production is not necessarily well correlated with total nutrients in the soil.

Of the total N in the system, 13 percent was found in the trees (*Table 2*). Nitrogen appears to be the most critical nutrient since a large portion of its total is in the biomass, and residual soil N becomes available at a rate of only 3 to 4 percent annually. The nearly universal importance of the N supply has been demonstrated

Table 2. Effect of harvest method on biomass and nutrients from a 16-year-old loblolly pine plantation.

Harvest method	Tree biomass		Nutrients in biomass						Nutrients in biomass expressed as a percentage of nutrients on site		
	Weight	Percentage	Weight			Percentage					
			N	P	K	N	P	K	N	P[1]	K[1]
	T/ha		—*kg/ha*—								
Debarked pulpwood to 8-cm top	102	53	74	13	61	23	27	27	3	3	9
Pulpwood to 8-cm top	116	60	104	14	80	32	29	35	4	3	12
Complete aerial	156	81	254	30	165	79	63	73	11	7	25
Complete aerial + roots 4 cm and larger	185	96	282	37	202	88	77	89	12	8	31
Total biomass aerial and below ground	192	100	321	48	226	100	100	100	13	11	34

[1] *Total in vegetation and forest floor and extractable in mineral soil.*

in many experiments showing trees responding to N fertilizer.

Determination of total P and K on similar sites shows that smaller proportions of P and K than of N are contained in the trees. The depletion rates of these elements, if based upon extractable P and K in the soil, do not reflect the true supply potential. Instead, depletion rate and nutrient availability are related to total supply and to the factors which control the rate of nutrient release. Even though the amounts of extractable P and K in soils are relatively low, trees have often failed to respond to addition of these elements, indicating that sufficient quantities become available for adequate tree growth.

Harvest-Nutrient Cycle Relationships

Several harvest options are open to the forest manager. Timber may be clearcut or thinned, and the biomass removed may range from debarked pulpwood to the entire tree including the large roots. It is important to consider the long-range effect of the options on site nutrients. Although all data presented are for a clearcut, various degrees of thinning would remove nutrients in proportion to the fraction of the stand that is harvested.

At about 16 years of age, highly productive plantations can be clearcut or thinned for pulpwood. In a 16-year-old stand, removal of needles, bark, branches, stems, and large roots would yield 185 metric tons/ha of biomass (*Table 2*). This material would contain about 80 to 90 percent of the nutrients in the tree biomass, and 12 percent of the total N, 8 percent of the extractable P, and 31 percent of the extractable K on the entire site. A much less drastic harvest alternative now generally employed, removing only the stemwood and bark to an 8-cm top, would yield 116 metric tons/ha. This form of harvest takes away only about one-third as much nutrients as total-tree harvest, but yields two-thirds as much biomass. Furthermore, the biomass left is mostly of low quality for manufacturing, and costs for manufacturing and waste disposal may exceed the return realized from its harvest. Removing only debarked pulpwood takes about 20 percent less N, P, and K from the site than a normal pulpwood harvest, and reduces the weight yield by only 10 percent.

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The effect of rotation length on the nutrient cycle should be considered along with biomass removal. In general, the longer the rotation, the more nutrients will be removed at any one harvest. However, because maximum nutrient accumulation occurs during the early stages of stand development, the shorter the rotation the greater will be the nutrient removal on an annual basis. In total-tree harvesting, the nutrient cycle will be less disrupted by long than by short rotations, owing to an increase in the proportion of biomass and nutrients in the stem with tree age, as well as the fact that the stem would be removed by any harvest alternative. If only pulpwood were removed, even short rotations would have little effect on site nutritional status. In this alternative the natural inputs from precipitation and geologic weathering would be able to nearly balance nutrient removal from the site, providing nutrients are not lost by nonharvest factors such as erosion or leaching.

The amount and number of times biomass can be removed before productivity is greatly reduced will vary by site. Sites with a relatively small proportion of their nutrients in the soil compared to the biomass—deep sands for example—may be rapidly depleted by complete tree harvesting. Conversely, some low-lying soils may be able to maintain production after many complete-tree harvests due to high nutrient reserves in the soil and replenishment by flooding.

Final Considerations

Nutrients are needed for the growth of vegetation. If large quantities are removed in any manner whatsoever, they must be replaced if vegetation is to grow at an acceptable rate. If we have complete-tree utilization, will the income from the material other than the bole be adequate for the replacement of depleted nutrients? A thorough appraisal of this question is necessary to insure sustained long-term forest production.

A complete biomass harvest followed by burning for site preparation could reduce site nutrients, especially N, to levels that will produce economically unacceptable tree growth after only a few rotations. Nutrient levels may be maintained by fertilization, but this practice is not likely to be economical. Moreover, one problem in fertilization is to supply nutrients in as useful and as longlasting a form as they are provided by the natural cycling processes. There is an optimum sustained annual biomass production for each site. This optimum production will depend on the ability of the site to provide nutrients and other factors required for growth, as well as on management practices imposed on the system.

The era of intensive culture we are now entering means more thought and care must be given to the soil. If we develop the required technology and can afford to replace all the nutrients removed from the site, then there may be no nutritional problems. But if we can not, then prudent removal of biomass from the site should be considered. ■

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